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A process model for force-controlled honing simulations

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Abstract

The selection of process parameter values for honing operations is challenging since their effect on the resulting surface characteristics is difficult to predict. With the right settings, the finishing operations can reduce surface roughness values, enhance the shape accuracy of bores and shafts, and create surface topographies with improved functional properties.
In this paper, a model for honing operations based on microscopic scans of tool topographies is presented. The model allows the simulation of material removal during the process by taking force-controlled honing operations into account.

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Keywords: Modelling; Simulation; Honing; Finishing; Force-Controlled; Machining

1. Introduction

Highly resistible surfaces can be manufactured by using finishing operations. These can reduce dimensional errors and affect the micro-topography of the surface. A typical application of long-stroke honing processes is the manufactur of cylinder liners where cylindricity can be improved and surfaces should contain deep grooves [1]. Short-stroke honing (finishing) operations reduce the surface roughness in order to enhance the functional properties of the workpiece [2]. Determining process parameter values that create a predetermined topography is difficult since the material removal process is complicated and the interrelation of the parameters is complex. Because of this, experimental investigations of finishing operations are necessary, and modelling the process is beneficial. First, a better understanding of the functional dependencies between the input parameter values and the result they produce helps to reduce the amount of time that is needed for process parameterization. Second, model-based simulation approaches allow for a virtual optimization process in order to avoid costly experimental investigations.

Models for the simulation of honing operations have been studied with very different key aspects. Numerical models for rotating tools have been used to simulate the dynamic tool behavior responsible for surface formation on the macroscopic scale [3]. Reizer et al. simulate the material removal process by applying filters and transformations to the measured data in order to predicted 2D profiles and 3D surfaces [4]. On the macroscopic scale, honing processes have been investigated in [5]. Another mathematical approach that takes many effects of the process into account is described in [6]. By using a numerical algorithm to simulate surface generation, tool dynamic and regenerative effects of the operation are accounted for.

A common problem of many modelling approaches is the abstraction of the honing operations either by mathematical transitions or by substituting the surface topography with their characteristic values, e. g. roughness. The potential for an increase in process knowledge and simulative prediction afforded by the availability of a honing process model motivates the research presented in this paper. The model developed is capable of describing material removal on a microscopic scale and computing process forces. This allows the transient simulation of force-controlled honing operations.

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2. Process Model

The basic requirements for a process model describing honing operations are a model for the tool, a model for the workpiece, and a method for computing the material removal process. In the following, both models are described and a material removal algorithm is presented that contains a model for the process forces.

2.1. Tool and Workpiece Models

Honing processes are surface preparation operations, and planar parts of a workpiece can be accurately represented by height values. Heightfields are grid-like structures with equidistantly arrayed entries representing the surface topography in a simple and compact manner. The surface is discretized and each parcel is associated with a floating-point number representing an exact height, neglecting an inherent limited computational precision in computer hardware. All entries contain relative values that are to be set in relation to some reference height. In contrast to the honing simulation presented in [7], the heightfield is mapped onto the cylindrical outer surface of the workpiece to avoid distortions.

A heightfield modelling the wall of a cylinder is shown in Fig. 1(a). Only a small area of the workpiece has been captured with confocal white light microscopy, yielding a local model in high detail with a very high resolution of 0.31 µm (Fig. 1(b)). This degree of precision is necessary because of the low roughness values that are to be expected in finishing operations. At this resolution, a model for a cylinder with diameter $r_{\text{workpiece}}$ = 25 mm and height h = 55 mm would require a memory size for values of type *float* of more than 330 GB. This size cannot be handled by current computer workstations and the use of the simulation would be questionable.

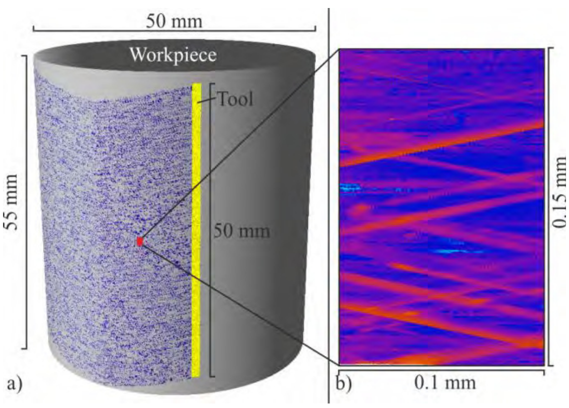

Fig. 1. (a) Complete workpiece model for a shaft and the current contact area of a finishing belt (yellow); (b) Model of a small area of the workpiece with higher precision.

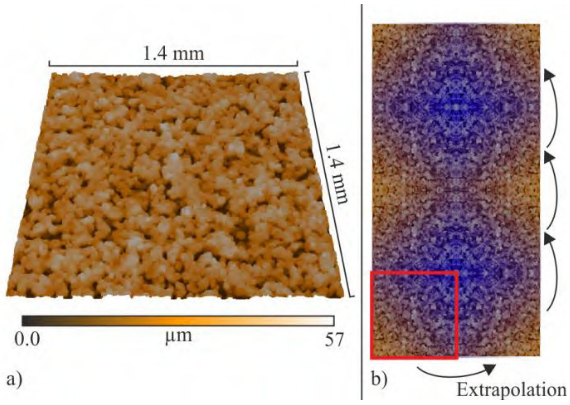

Fig. 2. (a) Captured height values of a finishing belt; (b) Complete model of the tool. The red marked area is extrapolated by mirroring to ensure continuity of the model. The color gradient visualizes the extrapolation algorithm using mirroring.

The tool model is based on three-dimensional scans of finishing belts for which heightfields are also created. Since scanning the tool is very time consuming, the tool model is enlarged and the height values are copied by consecutively mirroring them (cf. Fig. 2) over its surface. The tool model is limited to the contact zone of the finishing belt with the workpiece. In the contact zone, the tool is pressed onto the surface of the workpiece by a polymer roller and assumes the shape of the shaft. To simulate this, the height values of the tool are mapped onto a cylinder wall. A common problem associated with confocal white light microscopy is the introduction of measuring artifacts by reflecting surfaces and steep flanks, resulting in gaps and spikes in the heightfield data. While the former can be compensated for via interpolation, filter algorithms are required to repair the latter. For the simulation results described here the height values of the tool model have been clipped to a value that was determined by comparing the model with raster-electron images of the tool.

2.2. Time-Discrete Process Simulation

In the honing process, the workpiece rotates and the finishing belt oscillates axially. The combination of both movements results in the actual cutting speed. In the process simulation the cutting speed is emulated completely by the tool in order to avoid multiple moving objects in the visualization. Since no model for tool wear has yet been realized, the feed of the belt is neglected so that the whole operation is performed with a static tool model. The process simulation performs time-discrete simulation steps and calculates for each point in time the relative position of the tool. On top of the ongoing rotational and oscillatory movement of the tool, the reference radius r_{tool} can be modulated in order to take force-controlled honing into account. For each configuration, the tool-workpiece intersection is determined for each value of the workpiece heightfield.

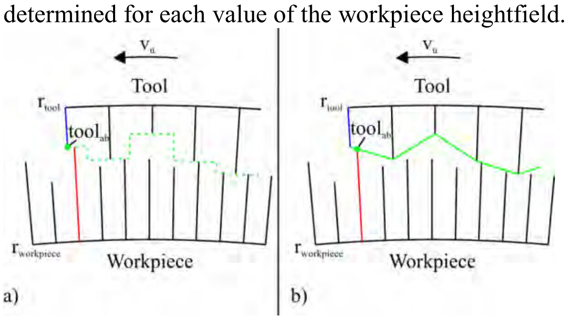

Fig. 3. Projection of height values to determine the tool intersection; (a) Nearest neighbor approach; (b) Bilinear interpolation of values.

The main requirement for a precise intersection is the assumption of a shared axis of rotation. This reduces the problem to two dimensions. For this, the angle and radius of the cylindrical coordinates of the workpiece are projected onto the reference radius of the tool. Fig. 3 displays the projection of the height values of the workpiece in order to determine the intersection with the tool uthing a nearest neighbor approach (Fig. 3(a)) or bilinear interpolation (Fig. 3(b)), depending on the precision of the tool model. With bilinear interpolation, the precision of the tool model can be reduced severely since planar parts of the tool surface are interpolated. In contrast to this, the nearest neighbor computation is faster but requires larger amounts of computer memory.

An important parameter of the simulation is the timestep. If the cutting increment, meaning the movement of the tool in one simulation step, is too large, the grains perforate the surface instead of creating continuous grooves. Previous investigations yielded good results if the cutting increment is equal to or less than the workpiece resolution along the circumference [7].

2.3. Material Removal Simulation

For each portion of the workpiece cut by the tool, its height value h is set to the corresponding height of the tool. This height value $tool_{ab,}$ at the position *(a, b)* of the tool model, is determined either by the nearest neighbor method or by bilinear interpolation of the four nearest values.

$$h = tool_{ab} + r_{tool} - r_{workpiece} + infeed \qquad (1)$$

A visualization for one dimension of the material removal is given in Fig. 3. Apart from considering different radii for the tool (r_{tool}) and the workpiece ($r_{workpiece}$), the current radial *infeed* of the tool has to be accounted for. Since the heightfield data does not contain any fixed reference height, the different radii occur as a result of the scanning technique. The old and the new value of each height are stored in a material-removal grid in order to analyze the engagement. Fig. 4(a) presents the material removal and Fig. 4(b) shows a sectional view of an exemplary row of the grid.

2.4. Force Calculation and Process Control

For each simulation step, the normal force must be calculated in order to model force-controlled honing processes. The force calculation makes use of an empirical force model developed by Kienzle [9], which has also been applied to predict process forces of milling processes [8] and grinding operations [10]. The Kienzle equation was developed for turning operations and estimates the cutting force based on reference experiments and the projected area of the uncut chip. Accordingly, for the force computation on an intersected height field, the uncut chip thickness must be determined in the effective cutting direction and is summed up afterwards.

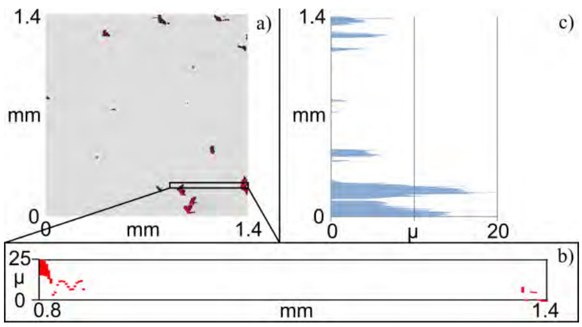

Fig. 4. (a) Material removal grid; (b) Sectional view through the grid; (c) Calculation of the difference of each row in the grid.

Given a movement of the tool along the x-axis, the difference between the maximum and the minimum value in each row of the material removal grid is computed. Fig. 4(c) displays these values for one row of the material removal. This simplified model neglects the effects of a larger grain tracing the path of a smaller grain. Fig. 4(b) shows such a situation with the smaller grain on the right and the larger grain on the left. Since only a small fraction of the tool surface contributes to material removal, as can be seen in Fig. 4(a), and this tracing effect is minimal, the effect on the computation of process forces is small.

For a precise force calculation, the computation of minima and maxima has to be performed in the effective cutting direction. To simplify this, the material-removal grid must be rotated to allow the computation of the chip thickness along the x-axis.

The intersection of the tool and the workpiece in the real process is controlled by an elastic roller that presses the finishing belt with a predetermined force onto the surface of the workpiece. Since the grains will produce deeper groves under increased pressure, the presence of an opposite force resulting from the cutting process is assumed. For this reason, the force calculation method described above is used to control the radial infeed of the tool. This technique eliminates the need to manually determine the relative positioning of the tool and the workpiece.

The calculation of the radial infeed is based on a predefined pressure p_{target} that has been used for the experiment and should be reached in the process. For each simulation step at time t, the increment of the infeed Δr_{inf} is determined:

$$\Delta r_{inf} = \Delta p_{smooth} \cdot cf \quad (2)$$

with the smoothed pressure difference

$$\Delta p_{smooth,t} = (1-\alpha) \cdot \Delta p_{smooth,\, t-1} + \alpha \cdot \Delta p_t, \quad (3)$$

where α is a weighing factor to smooth fluctuating forces and

$$\Delta p_t = p_{sim,t} - p_{target}. \quad (4)$$

For this, p_{sim} is the computer-simulated force per mm² and cf is used in order to regulate the process. For further experiments, cf has been set to 0.0001 manually. Larger values result in a more direct correction but the simulation becomes unstable for large pressure gradients. Smaller values delay the correction of the infeed but smooth the dynamic behavior of the control.

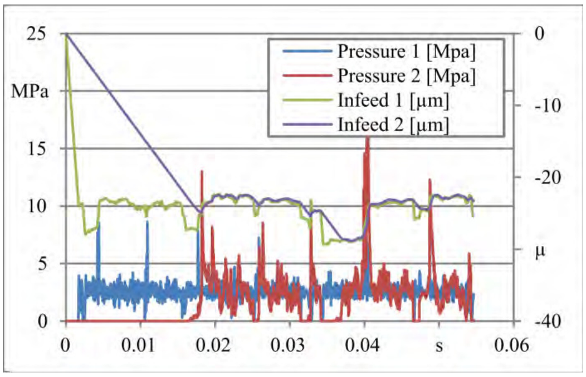

Fig. 5. Simulated pressure and the resulting infeeds for $\alpha = 0.5$ and $cf = 0.0001$ mm/MPa (Pressure 1) and $cf = 0.00001$ mm/MPa (Pressure 2) respectively.

Fig. 5 shows a plot of process pressure from the simulation and the resulting infeed. As can be seen, the infeed is controlled in a way that the difference between the predefined target pressure of 2.54 MPa and the simulated pressure is minimized. The noise in the force run results from the reaction of the control mechanism to changing engagement conditions. After the initial engagement of the tool, where a very small value for the infeed had been selected, no further instability occurs.

3. Experimental Investigation

For the calibration of the simulation system and a comparison of the simulation output with real results, experiments have been performed covering the most important process parameters. By using a central composite design (CCD) for the experimental investigations, a total of 19 experiments have been conducted. Shafts of unhardened 100Cr6 were ground to a defined diameter of about 50 mm. The prepared workpieces were then micro-finished with a finishing belt with elutriated AlO_2 grains of size 30 µm. The experiments were conducted without a lubricant by using a Supfina finishing device that was mounted onto a MAG Boehringer M 670 turning machine which is shown in Fig. 6.

Table 1. Parameter ranges for the design of experiments.

Parameter	Minimum	Maximum
Time t [s]	10	60
Speed v_u [m/min]	5	125
Pressure F [N]	60	540
Belt Feed v_b [mm/min]	6	64

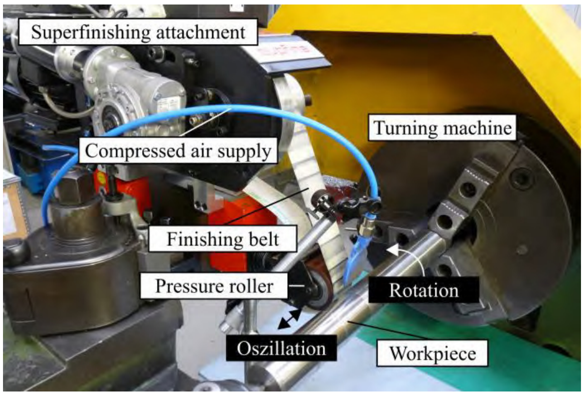

Fig. 6. Experimental setup

The process parameters that have been varied are listed in Table 1. As described in section 2.2, the feed of the finishing belt is neglected in the process model. For all simulations, the pressure was divided by the contact area between the tool and the workpiece of 69.9 mm². This is necessary since, due to performance reasons, the tool may only partially remain in contact with the workpiece. In all experiments, the belt oscillates at 21 Hz in the axial direction with an amplitude of 2.5 mm. Thus, the height of the tool model has to be at least as high as the workpiece model plus 2 x 2.5mm = 5 mm.

The topography of the initially ground surface of the workpieces was captured by confocal white-light microscopy and used as initialization for the workpiece model. Profiles of the resulting surface of each experiment were captured tactilely along the rotational axis.

4. Simulation Results

The setup of the simulation parameters is important in order to create a model that is capable of predicting experimental results. In the following, a tool model of size 5.6 mm x 1.39 mm (precision 0.61 µm) is used for all simulations. With this configuration, in every revolution, the tool intersects the workpiece. The size of the workpiece model is very important for the computation of process forces and the infeed control. An ideal size would cover the complete height of the workpiece and a minimum of two times the width of the contact area. With this configuration, the engagement of the tool and the workpiece covers the whole contact area and the dynamic infeed regulation stabilizes before the material removal takes place on the core region of the workpiece model. When smaller models are used, the engagement is influenced by single grains of the tool model which collide with the workpiece causing very abrupt changes in the simulated force. For a simulation with a minimal workpiece model consisting of only one column, which is sufficient for the computation of a profile and roughness values, no stable infeed control can be reached.

In order to examine the presented process model, the parameter values for the force computation and the resulting radial infeed must be investigated. Based on the infeed data, profiles have to be generated that are comparable to those used in the experiments conducted. The linear term k_c of the Kienzle equation

$$\cdot \quad \cdot\left(-\right)^{1-m}, \qquad (5)$$

represents a simple correspondence between the pressure and the engagement height of one row of the material removal grid. In contrast to this, the exponent m of the formula takes the progressive pressure-to-infeed ratio into account. Experimental results with different pressures were used in order to determine the correct exponent for the Kienzle equation.

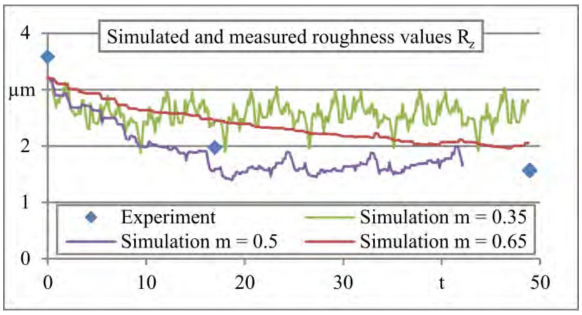

Fig. 7. Simulated and measured roughness values over the process time. Simulation were run with a value of k_c = *5000*.

Fig. 7 presents the roughness values R_z during the process simulation for four different values of m. It can be seen that the absolute roughness values as well as the trend during finishing matches the measured data. The simulation were run with a fixed value of $k_c = 5000$. This value can be used to calibrate the simulation in order to account for different process pressure values. For future investigations, an extensive comparison must be performed to reveal the influence of the parameter

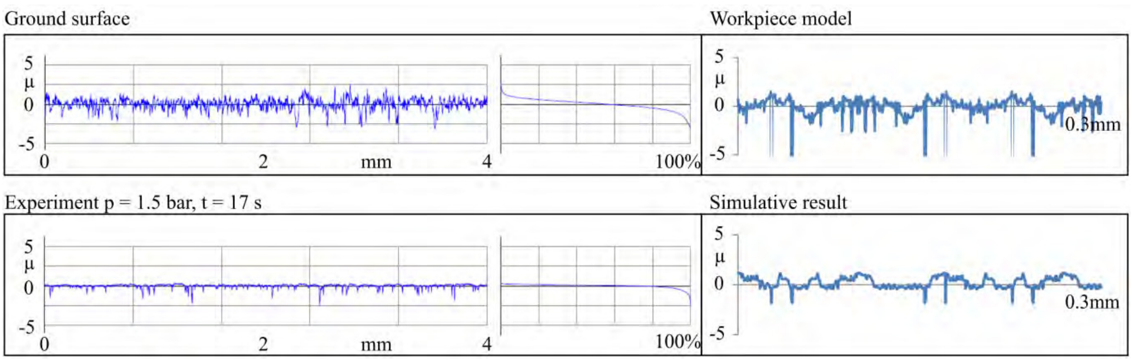

Fig. 8. Example of an experimental result and the corresponding setup in the simulation environment. After the simulation of the finishing process, the profile values have changed as well as the roughness.

values on the simulation results.

Fig. 8 displays the initial tactile scan of the workpiece and the actual workpiece model in the simulation. After the simulation of the finishing operation, the roughness value has decreased in the experiment from $R_z = 3.93$ to $R_z = 1.97$. The corresponding roughness values on the workpiece model, which is significantly smaller than the measured distance, have been changed from $R_z = 6.48$ to $R_z = 2.91$.

The determination of the simulation settings is highly dependent on the workpiece material which must be investigated in future research. However, the first simulative results are promising.

5. Conclusion and Future Work

In this paper, a microscopic material-removal model and a model for force-controlled honing operations are presented. Based on three-dimensional microscopic scans of tools and workpieces, corresponding models are created and a direct intersection routine is described. With these, the transient manipulations of the workpiece surface are simulated and the effects of different process parameter values can be reproduced.

An existing problem is the computational complexity of the intersection routine, even in cases where a simple material removal is computed. Since the models do not fit entirely into the caches of modern CPUs and because of the very precise models required, an excessive amount of intersections has to be computed. Because of the nature of the task, the algorithm has a high potential for parallel execution and benefits from multiple CPU cores. Moreover, it is possible to use the GPU of a graphics adapter to increase the simulation speed. The first tests with a parallel implementation using a GPU resulting in simulations which were 100 times faster than those utilizing a CPU-based implementation.

Continuing investigations into the simulation parameters regarding the force model and infeed control will be made, and an analysis of the pressure and cutting speed process parameters will be performed. The necessity of using a model for tool wear should be investigated as well.

Fig. 9 displays the tool model with the amount of material removed for each parcel mapped to a color scale. As can be expected, only a small portion of the grains is responsible for the material removal. These data could be used to determine the grain most likely to be damaged in the process. Thus, tool wear could be accounted for with this model.

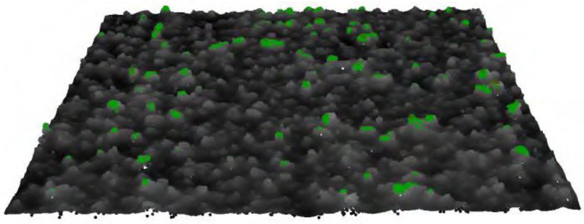

Fig. 9. Model of the tool with color-coded amount of removed material for each height value.

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